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A 2-Liter, 2000 MPa Air Source for the Radiatively Driven Hypersonic Wind Tunnel

M. Costantino, D. Lofftus

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ABSTRACT. The A2 LITE is a 2 liter, 2000 MPa, 750 K ultra-high pressure (UHP) vessel used to demonstrate UHP technology and to provide an air flow for wind tunnel nozzle development. It is the largest volume UHP vessel in the world. The design is based on a 100:1 pressure intensification using a hydraulic ram as a low pressure driver and a three-layer compound cylinder UHP section. Active control of the 900 mm piston stroke in the 63.5 mm bore permits pressure-time profiles ranging from static to constant pressure during flow through a 1 mm throat diameter nozzle for 1 second.

1 INTRODUCTION

The Radiatively Driven Hypersonic Wind Tunnel (RDHWT)[1] design concept for the Medium Scale Hypersonic Wind Tunnel (MSHWT) requires an ultra-high pressure (UHP) air source. The UHP section must have pressure-temperature conditions to provide about 30-40% of the total enthalpy in the process at low entropy, and must have a volume large enough to meet mass flow rate and flow time requirements. The present design point for the MSHWT UHP source is 2300 MPa (333,500 Psi) and 750 K, with a flow time of 1 second at a flow rate of about 165 kg/s. The latter translate to a UHP volume of about 150 liters. References 2 and 3 contain a discussion of the design concept for the UHP source for both the MSHWT and a full-scale test facility.[2,3]

The "A2 LITE" is a UHP technology demonstrator and an air source for nozzle survivability experiments. The 2000 MPa, 750 K operating point in an initial volume of 2.17 liters makes it the largest UHP ($P > 1500$ MPa) pressure vessel in the world. An active control system provides an operational envelope of $0 < P < 2000$ MPa, $300\ K < T < 750\ K$ for pressure-time profiles from static to constant pressure flow through a 1.4 mm diameter nozzle for 1 s. The design manages programmatic risk by using accepted engineering practices and Environmental, Safety, and Health risk by containing energy sources in ASME-rated containers or in engineered barricades.

This article is a description of the design of the A2 LITE and its supporting systems.

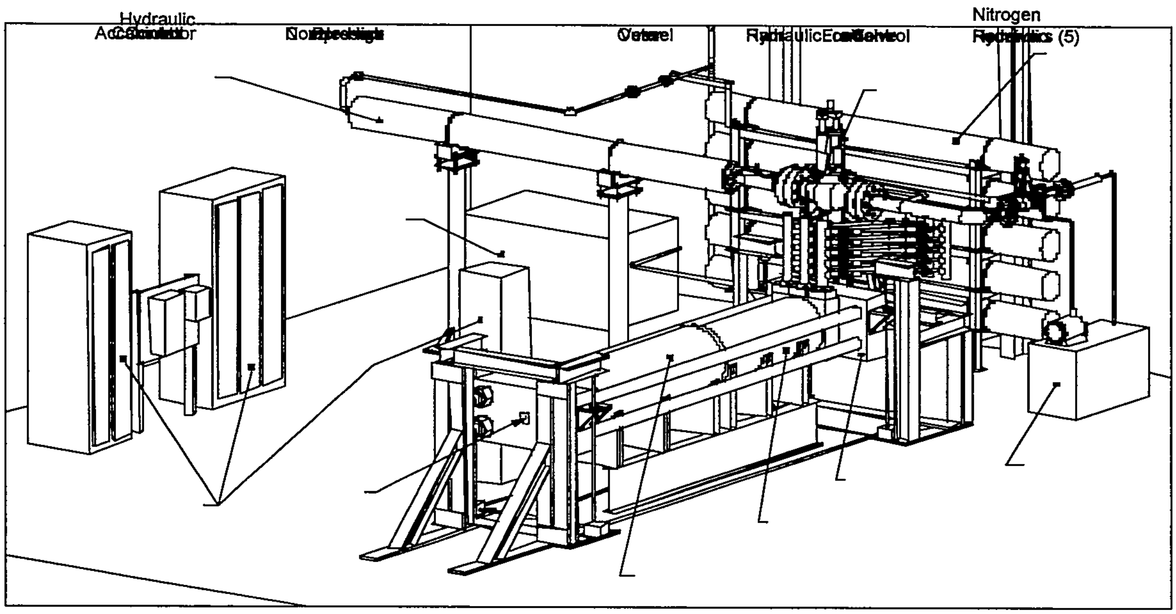

Figure 0 Schematic of the Ultra-High Pressure Test Facility at MSE-TA. For scale, the Outer Vessel is 2440 mm long and 914 mm in diameter.

2 A2 LITE SYSTEM OVERVIEW

2.1 *General*

The A2 LITE is comprised of seven major components (Figure 1): 1) a nitrogen manifold that stores about $5(10^7)$ Joules in 35 MPa, room temperature nitrogen; 2) a gas/hydraulic fluid accumulator that converts the stored gas energy to hydraulic fluid energy; 3) two, fast acting, high flow valves that control the flow of hydraulic fluid into a hydraulic ram; 4) a hydraulic ram that converts 35 MPa hydraulic fluid to a 7.5 MN force over a 900 mm stroke; 5) a UHP vessel that contains the working gas; 6) a load frame that reacts the pressure forces; and 7) a control system that provides active control of the pressure in the UHP vessel with a time resolution of the order of 10 ms.

In operation, the working gas in the UHP intensifier is pre-pressurized and heated to bring the gas to an entropy equal to the entropy at the final plenum operating pressure and temperature. The bounding value for this initial state is 300 MPa and 450 K. Over a time of about 0.5 s, energy is transferred under active control from the nitrogen storage manifold through the fast valves to the hydraulic ram to accelerate the hydraulic ram piston to the desired constant speed. The hydraulic ram drives the UHP piston into the plenum, decreasing its volume and increasing the pressure to provide the desired pressure *vs.* time profile. A valve at the nozzle opens at a pre-determined time to initiate the flow. At the end of the approximate 1 second constant pressure flow, the hydraulic fluid is vented and the residual working gas pressure causes the piston to stop.

2.2 *UHP Intensifier*

The UHP intensifier (Figure 2) is a subassembly comprised of the UHP vessel, an outer vessel, a hydraulic ram, and an external load frame. Section 3 contains a description of the UHP vessel. The outer vessel is a cylindrical A36 steel shell 2438 mm long, 914 mm outside diameter (OD) with a 76 mm wall thickness. It aligns the UHP vessel with the hydraulic ram and is a barricade to contain radial

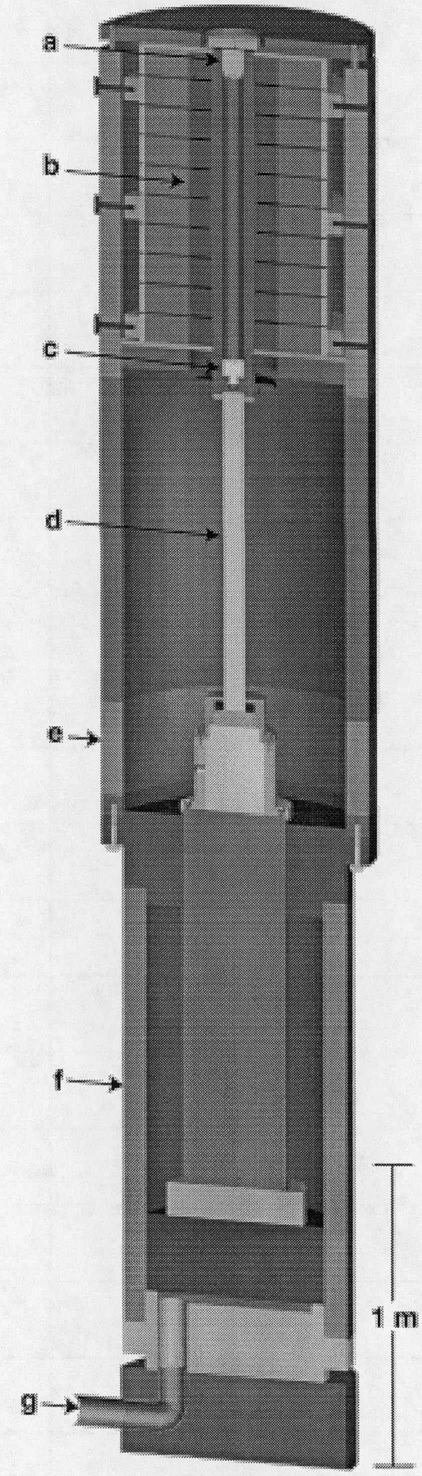

Figure 2. The A2 LITE UHP Intensifier. The major components are: (a) Nozzle end closure; (b) UHP vessel; (c) Moving seal; (d) UHP piston; (e) Outer vessel; and (f) Hydraulic ram. Hydraulic fluid enters through a manifold shown schematically at (g).

blast and fragments. A portion of the shell is removable to permit easy access to the UHP piston and various diagnostics. The hydraulic ram is a commercial (Model SH24x36HPC, Service Hydraulics, Auburn, WA) design having a 610 mm diameter low pressure piston and a 356 mm diameter ram with a 914 mm extension. The overall retracted length of the hydraulic ram is 2134 mm. The ram produces 10 MN force at a hydraulic operating pressure of 34.5 MPa. At full extension, the angular tolerance of the ram piston from its reference axis is 0.03 degrees to control the eccentric load on the UHP piston. The external load frame is a four post design with an open space 1067 mm wide and 5500 mm long with four, 152 mm diameter, AISI 1045 steel tie rods.

2.3 *Energy Storage and Transfer*

Approximately 56 MJ of isentropic expansion energy is stored in 34.5 MPa room temperature nitrogen in five ASME-stamped cylinders (Tobul Accumulator, Bamberg, SC); each 4994 mm long, 406 mm OD, 305 mm ID with a 341 liter volume. The cylinders are charged using a commercial pump (Model C45-7.5-2FX, Hydro-Pac, Inc., Fairview, PA), drawing nitrogen from a liquid nitrogen boil-off manifold. The nitrogen storage system is sized to provide positive control of the flow through the fast acting valves over a full operational cycle.

A 1:1 accumulator/separator (Model 16A50-720, Tobul Accumulator, Bamberg, SC) having a working volume of 340 liters converts gas energy to hydraulic fluid energy. The hydraulic side of the separator, with the piston fully displaced, contains enough fluid to fill the hydraulic ram at its full displacement. In preparation for an operational cycle, an auxiliary hydraulic pump pressurizes the separator and the piping volume between the separator and the fast acting valves to a pressure greater than the nitrogen pressure in the storage system. This forces the nitrogen in the separator to flow back into the storage system and provides the initial upstream hydraulic pressure at the fast acting valves.

Two fast acting, air actuated globe valves (Model 2500CL Mark One, 2" and 6"; Flowserve Corp, Valtek Control Products, Springfield, UT) are in parallel between the separator and the hydraulic ram. The combination of 2" and 6" valves provides control for flow rates between 0.6 and 200 liters/s. The valves have a response time of 200 ms full-closed to full-open. A manifold of 15, 2" flexible hoses connects the downstream side of the valves to the hydraulic ram.

2.4 *Instrumentation and Control*

The instrumentation and control system is based on National Instruments computer hardware and software. The status and interlock architecture supports the various modes of systems checks and operational cycles. A commercial application, EASY5 by Boeing Co.,[4] is used to model the gas/hydraulic system from the nitrogen storage tanks to the working gas exiting the nozzle. The code includes the real gas Equations of State for nitrogen, helium, and air.

An input profile for UHP piston displacement, UHP piston speed, or working gas pressure *vs.* time is compared to the appropriate diagnostic to generate an error signal. The signal actively controls the flow through the main or trim control valves. Section 5.1 is a discussion of the control system.

3 UHP VESSEL

The UHP vessel (Figure 3), the largest volume UHP (greater than 1500 MPa) vessel of which we are aware, is a three layer, open ended compound cylinder. A fourth layer, a 304 stainless steel safety ring, absorbs elastic strain energy upon failure of one of the inner three layers. The vessel has a 63.5 mm inside diameter; an overall 635 mm outside diameter; and is 1130 mm long. The working volume is 2.17 liters.

Layer 1 is a monolithic, thick walled cylinder of 350-grade maraging steel. The material provides the highest strength, both at ambient and at temperatures to about 800 K of the super alloys. Additionally, it provides reasonably good oxidation resistance, is economically machinable, and is reliably heat treatable in arbitrarily large sections. There was no measurable shape change of the 63.5 mm diameter bore over the 1130 mm length of the part as a result of heat treating, although the part did decrease in length by about 1.4 mm. The outside surface has a biconical, 1° taper from a maximum of 152 mm diameter at the mid-plane. This outside diameter is determined by the availability of certified-property billets of the 350-grade material, and constrains the overall geometry of the UHP vessel.

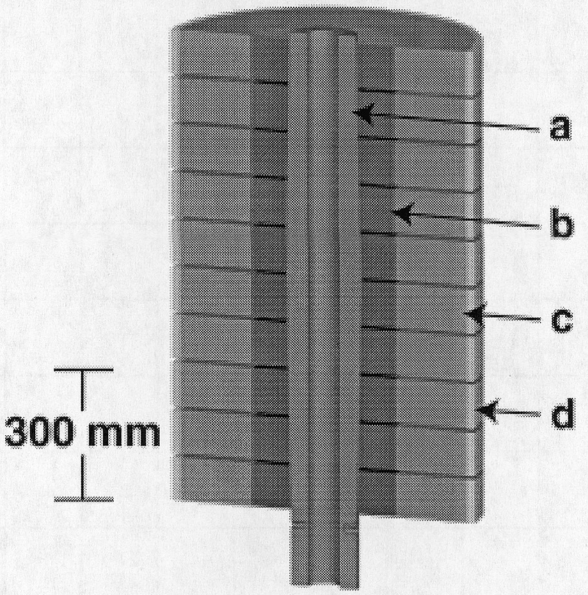

Figure 3. The A2 LITE UHP vessel. The compound vessel is comprised of three layers: (a) 350-grade maraging steel Layer 1; (b) AISI 4340 steel Layer 2, (c) AISI 4340 steel Layer 3, and (d) 304 stainless steel safety ring.

Layer 2 and Layer 3 are AISI 4340 rings 92 mm thick, heat treated to R_c50 and R_c45, respectively. Five rings are pressed onto each of the conical OD surfaces of Layer 1. Use of the ring design results in increased costs owing to a larger number of parts, but presents the advantages of smaller sections for heat treating quality and use of available equipment for assembly. It also permits optimization of the compound cylinder design as the diameter ratio of Layer 1 decreases along its length. The Layer 2/ Layer 3/ safety ring subassembly is press-fitted together in a 2.6 MN load frame using MolyKote Gn paste as a lubricant. Each of the ten rings then is pressed onto the Layer 1.

The interferences between the layers are optimized for the nominal 2000 MPa, 750 K operating condition using a computer code by Huddleston.[5] The code provides optimal diameter ratios and interferences for multi-material compound cylinders with user-input pressure and thermal boundary conditions. It is based on elastic Lame theory and uses the von Mises failure condition.

3.1 *End Closures*

The static end closure (Figure 4) is a common design that employs an inverted Bridgman seal. Eight, 20° Bridgman cone feedthroughs are used to extract a four-terminal manganin pressure gauge signal and two thermocouple signals. A check valve assembly along the axis of the end closure permits relief of residual pressure in the event the moving Bridgman seal does not retract to a point below the gas inlet. At these extreme gas pressures, the axial load chain (the end closure, moving seal, and the UHP piston) are in uniaxial compression and are the components that limit the operating pressure. The static end closure is made of 300-grade maraging steel at R_c55 to provide a room temperature ultimate tensile strength of 2025 MPa and a 0.2% offset yield strength of 1980 MPa. These strengths degrade by 25-30% at a uniform temperature of 750 K.

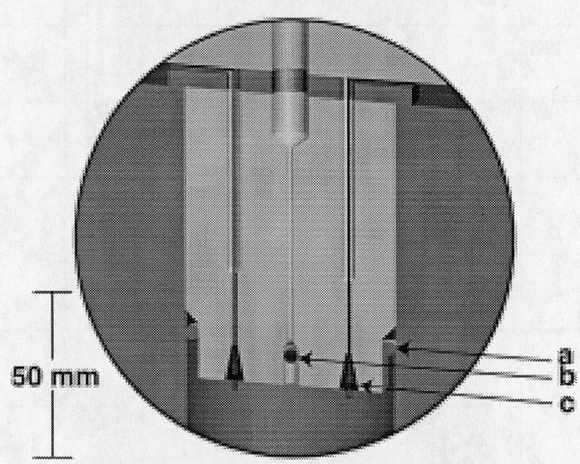

Figure 4. UHP vessel diagnostics end closure. (a) Inverted Bridgman seal, (b) Check valve, (c) Eight electrical feedthroughs for gas pressure and temperature measurements. In the nozzle end closure version, the check valve is replaced with a conical nozzle insert

3.2 *Moving Bridgman Seal*

The moving Bridgman seal is a standard, "mushroom" design with indium-coated, steel anti-extrusion rings and an SP polyimide (Vespel®, DuPont Corp., Newark, DE) packing. Although this type of seal is highly reliable, the compound cylinder, fixed radial support design of the pressure vessel and the extreme pressures require careful attention to the radial clearance between the seal components and the pressure vessel bore.

In operation, the soft coating material on

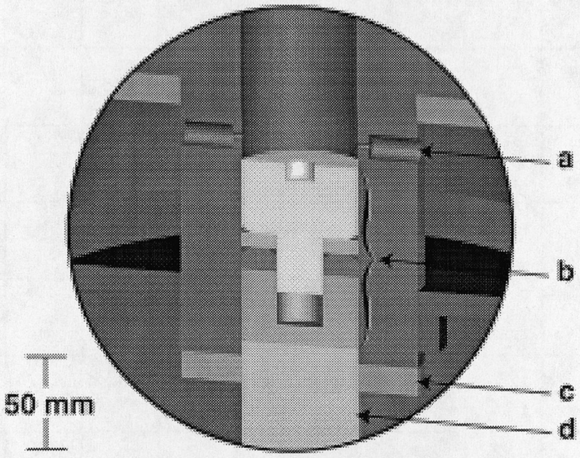

Figure 5. (a) Gas input to the UHP vessel, (b) Bridgman moving seal assembly consisting of the mushroom, anti-extrusion rings, packing, follower, and base, (c) Alignment bushing to locate the UHP piston, and (d) UHP piston.

the anti-extrusion rings and the packing material are in contact with the pressure vessel wall, which has a high heat capacity and nominally is at 750 K. The friction work deposits additional heat into those components. Calculations indicate that the packing material will survive over the temperature-time profile for a 2000 MPa, 750 K operational cycle. Although the relative hardnesses of the anti-extrusion rings and the pressure vessel bore do not demand lubrication, a thin layer of a soft metal helps prevent leaks though shallow scratches. The ring coating both melts and extrudes, but remains bonded to the metal rings adequately to serve this purpose, and to provide lubrication.

3.3 *UHP Piston*

The UHP piston length-to-diameter ratio is driven by the requirement to maximize the working volume, constrained by the 150 mm nominal OD of the Layer 1. Failure in uniaxial stress and in elastic buckling both are addressed by use of Kennametal KF310 (Kennametal Engineered Products Group, Latrobe, PA); a tough, fine-grained 10% Co, 0.2% V tungsten carbide, having an elastic modulus of 580 GPa, an ultimate compressive strength of 4.54 GPa, and a Transverse Rupture Strength of 3.11 GPa.[6] The piston is a cylinder 63.40 mm in diameter and 1041.4 mm long. An interference fitted binding ring at its base ((b) in Figure 6) provides both a compressive radial stress to mitigate shear failure and to provide a means of extracting the piston from the pressure vessel. A collar assembly provides the axial load for extraction and permits limited lateral motion of the piston under load, creating the free end of the column. A thin lead foil lubricates the piston-piston anvil contact surface. A location fit bushing at the entrance to the pressure vessel ((c) in Figure 5) provides the pinned end boundary condition for buckling.

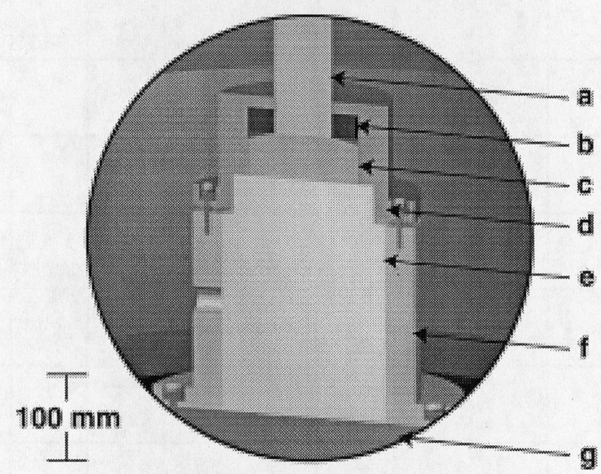

Figure 6. Load chain detail at the hydraulic ram. (a) UHP piston, (b) Binding ring, (c) Anvil, (d) Collar, (e) 9 MN load cell, (f) Load cell housing, (g) Hydraulic ram piston

A Kennametal KF310 anvil with a 7° bevel distributes the load on the piston over the load button of a 9 MN load cell (Model

MPB/G400-01, Sensotec, Inc., Columbus, OH), which is fitted to the piston of the hydraulic ram.

4 ULTRAHIGH PRESSURE TEST FACILITY

Figure 1 shows a view of the Ultra-High Pressure Test Facility at MSE-TA, Inc. in Butte, MT. The xxx m^2 laboratory space is blast-rated for xxx lbs equivalent TNT energy. Operations at pressures greater than 40 MPa are executed remotely from a control room outside the blast-protected area. The normal operational cycle blowdown through the nozzle results in noise levels in excess of 140 dB for more than 1 second.

In a typical experiment cycle, approximately $5(10^7)$ J energy for the process is stored in five receivers, each with 340 liters nitrogen pressurized to 29 MPa using a 310 MPa compressor. An auxiliary hydraulic pump (Hydra Power Systems, Portland, OR) moves the separator piston in the gas/hydraulic accumulator, raising the gas pressure in the receivers to 34 MPa. Service air (0.7 MPa) moves the piston of the hydraulic ram to its fully retracted position. The 310 MPa compressor then pre-pressurizes the UHP vessel to the desired starting pressure to complete preparation for the cycle. The remainder of the cycle is controlled manually or automatically using the control system described in the next section.

5 CONTROL SYSTEM AND PROCESS MODLEING

5.1 *Control System*

The UHPTF control system uses National Instruments LabView software as a graphical environment for the data acquisition system (DAQ), the instrumentation and control system, and the human-machine interface. The Supervisory Control Module is used for I/O configuration, data logging, alarm and event management, programmable logic controller (PLC) connectivity, and DAQ initiation. Three computer stations, the Computer Operator Station (COS) in the control room, the Remote Computer Operator Station (RCOS) in the test bay, and the Remote Monitoring Station (RMS) for real-time viewing of data in the control room are networked using Ethernet Media 10 Base-T. Field connections are made using an Allen Bradley PLC, which contains analog and discrete input and output cards connected to field instruments and equipment, ladder logic control code, and Ethernet communications connectivity.

There are two control modes: 1) manual control to perform low speed movement of the UHP piston and 2) automatic control to perform all other cycles. A single-loop analog controller controls the 6-inch and the 2-inch hydraulic valves using a proportional-integral algorithm. The control loop can be configured to use UHP piston velocity, piston position, or hydraulic ram pressure as the controlled process variable. This loop uses a Modicon Momentum PLC (Model 171CCC98020, Schneider Electric Co., Paris, France) as a standalone setpoint generator that provides a 4 – 20 mA output signal to the analog controller for use as a reference signal. Setpoint values for the full operational cycle are downloaded to the PLC before the start of a cycle using an Ethernet connection. The rate of setpoint changes from the PLC to the analog controller is set to 10 msec.

A standalone Modicon PLC provides a separate safeing system for the test facility. Its purpose is to monitor selected parameters; including piston position, piston speed, piston acceleration, and ram pressure, for out of range conditions. The PLC compares values of those four parameters, set based on the expected response for each cycle, to preset alarm limits. If an alarm limit is exceeded, an output contact closes and sends a signal to close the hydraulic control valves at their maximum rate of 200 msec from full-open to full-closed.The A2 LITE is fully instrumented for pressure, temperature, acceleration, position, speed, strain, flow, and load. There are approximately 75 instruments and control valves under computer control, including those on vendor-provided equipment, such as the gas compressor and the hydraulic pump. Eighty data channels from the intensifier are acquired using a National Instruments DAQ system in a standalone cabinet in the test bay. The DAQ processor is a client of the COS and RCOS on an Ethernet local area network. Four DAQ cards make four types of measurements at different rates: 1) up to 64 thermocouple measurements at a maximum rate of 5,000 samples per second, 2) up to 32 thermocouple measurements at a maximum rate of 10,000 samples per second, 3) up to 32 strain gauge/bridge measurements at a maximum rate of 10,000 samples per second, and 4) up to 32 differential or 64 single ended low voltage measurements at a maximum rate of 10,000 samples per second. A discrete timing signal from the main control computer initiates the DAQ system during a cycle.

5.2 *Process Modeling*

A commercial dynamic modeling/simulation software package, EASY5 (Mechanical Dynamics, Ann Arbor, MI), is used to develop hardware specifications and to model system performance. EASY5 features a graphical user interface coupled with predefined models which are used as building blocks to create complex models with relative ease. The user-defined gas feature models the real gas properties of air, nitrogen, and helium to pressures of 2000 MPa at temperatures from 280 K to 2000 K. Parameter changes, including initial conditions, do not require rebuilding the model, allowing rapid parametric design studies. Any computed variable may be plotted versus time or any other computed variable as the simulation proceeds.

Detailed models have been created for the nitrogen receivers, hydraulic accumulator, control valves, hydraulic ram, and UHP vessel (including the nozzle). The analog control system for the hydraulic control valves also is modeled in some detail. Simulations show that the system performance is governed by the performance of the hydraulic control valve, resulting in a significant effort to procure a suitably fast and accurate valve.

A representative result from the EASY5 simulation is shown in Figure 7 for the case of a high-velocity, high-pressure cycle in the velocity control mode. The velocity profile used as a control ramped linearly to 0.5 m/s (20 inches /sec) over the first 0.35 seconds, held this velocity for 1.4 seconds, and then ramped down to zero in 0.05 seconds. A small disturbance is seen just as the valve first opens due to entrained air, which is included in the model. The piston velocity lags the input profile as the valve continues to open and hydraulic fluid flows. As the pressure in the UHP vessel increases, the control system has trou-

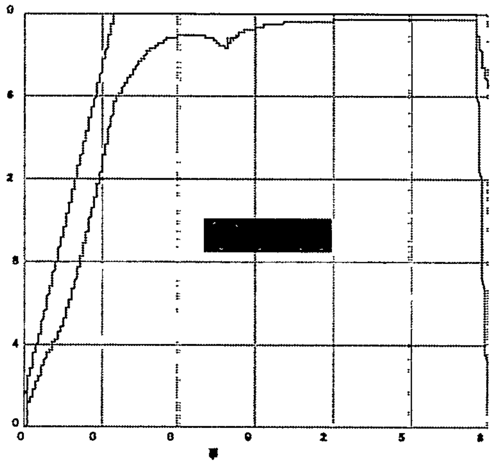

Figure 7. Typical output of a simulation using EASY5. The dashed line is the control velocity for the UHP piston and the solid line is the model simulation. The rupture disk that opens the nozzle to flow functions at about 0.78 s at 2000 MPa.

ble with the increasingly incompressible gas (the model uses a real gas Equation of State) and piston velocity slows until the rupture disk at the nozzle exit opens at 2000 MPa at 0.78 seconds into the simulation. The high gains in the control system result in a small amount of ringing just after the rupture disk opens. The velocity profile is quite flat during the remainder of the cycle, while the working gas (nitrogen for this example) flows out through the nozzle. At the end of the stroke the velocity is decreased and the hydraulic control valve is closed at its maximum rate.

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